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An investigation into the short-circuit characteristics of Sic MOSFET power devices

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Abstract. Silicon carbide (SiC) metal-oxide-semiconductor field-effect transistor (MOSFET) devices exhibit substantial prospects for application under extreme operational conditions, including elevated temperatures, high voltages, and high frequencies. Nevertheless, owing to their distinctive material and structural attributes, SiC MOSFET devices are not devoid of challenges, with the short-circuit phenomenon constituting a pivotal avenue of inquiry. The short-circuit effect pertains to the abrupt escalation of leakage current that these devices might undergo under elevated voltage conditions, thereby exerting a perturbing influence on their stability and reliability. Investigations into the short-circuit effect predominantly revolve around two dimensions: one involves comprehending its underlying physical mechanisms, while the other centers on identifying commensurate remedial approaches.With respect to the underlying physical mechanisms, researchers have discerned that the elevated breakdown field strength and augmented carrier mobility intrinsic to SiC materials engender an augmentation in leakage current, consequently giving rise to the short-circuit effect. Furthermore, factors such as oxide layer anomalies and surface states are also conceivable catalysts for the surge in leakage current. To rectify this predicament, scholars have proffered a panoply of stratagems, encompassing the optimization of material synthesis processes, enhancement of oxide layer quality, refinement of device structural designs, and incorporation of protective circuitry, among others. In summation, the investigation of the short-circuit effect in silicon carbide MOSFET devices is fundamentally aimed at attaining an in-depth comprehension of its causative mechanisms. Moreover, it endeavors to proffer efficacious resolutions conducive to augmenting the reliability and steadfastness of these devices within high-temperature and high-voltage environments, thereby facilitating their widespread integration within the ambit of high-performance power electronics.

Keywords: Silicon carbide (SiC) MOSFET, high temperature, short-circuit effect, reliability.

1. Introduction

With the continuous advancement of modern technology, high-performance power electronic devices are increasingly employed across various domains such as industry, transportation, and energy [1]. In this realm, Silicon Carbide (SiC) Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) devices have garnered considerable attention due to their exceptional performance under extreme conditions like high temperature, high voltage, and high frequency. In contrast to conventional Silicon (Si) MOSFET devices, SiC MOSFET devices offer heightened breakdown electric field strength, increased carrier mobility, and reduced conduction and switching losses, bestowing them with significant advantages in high-performance power electronic conversion [2].Nonetheless, despite the multitude of benefits associated with SiC MOSFET devices, they still grapple with several challenges and issues in practical applications, with one of these being the short-circuit effect..

The short-circuit effect, as a salient concern surrounding SiC MOSFET devices, directly impacts their stability, reliability, and long-term operational performance. The short-circuit effect refers to a sudden surge in leakage current when the device is subjected to high voltages, and in some cases, even results in uncontrolled behavior. This not only leads to a deterioration in device performance but also has the potential to induce equipment damage or failure. The presence of the short-circuit effect not only restricts the application of SiC MOSFET devices in high-temperature and high-voltage environments but also limits their performance during high-frequency operations. Consequently, in-depth investigation into the short-circuit mechanism of SiC MOSFET devices and the exploration of effective suppression methods hold paramount significance in driving the advancement of high-performance power electronic devices [3].

The primary objective of this paper is to systematically explore the occurrence mechanism, influencing factors, and potential solutions for the short-circuit effect in SiC MOSFET devices through comprehensive research. Firstly, we will review the characteristics of SiC materials and the structure and operational principles of SiC MOSFET devices, thus establishing a foundation for comprehending the short-circuit effect. Subsequently, we will delve into the physical mechanisms of the short-circuit effect, including the impact of material's high breakdown field strength and augmented carrier mobility on the surge in leakage current, as well as the potential contributions of oxide layer defects and surface states to the phenomenon. Following that, we will introduce existing methods for short-circuit effect mitigation, such as optimization of material fabrication processes, enhancement of oxide layer quality, optimization of device structural design, and the incorporation of protective circuits. Lastly, we will summarize the existing research achievements and outline the future directions in SiC MOSFET short-circuit effect research, offering valuable insights for enhancing the reliability and performance of SiC MOSFET devices [4].

In conclusion, the study presented herein aims to thoroughly investigate the short-circuit effect issue in SiC MOSFET devices, providing technical support and solutions for their application in the high-performance power electronic domain, and fostering the development of scientific research and engineering practices in related fields [5].

2. Short-Circuit Mechanism

Silicon Carbide (SiC) Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) devices, as high-performance power electronic components, have garnered widespread attention for their application in high-temperature, high-voltage, and high-frequency environments [6]. However, the practical implementation of SiC MOSFET devices is often constrained by the occurrence of the short-circuit effect, which exerts a significant impact on device performance and reliability. This section undertakes an in-depth exploration of the underlying mechanisms governing the short-circuit effect in SiC MOSFET devices, with a specific focus on factors linked to their unique material and structural attributes

The manifestation of the short-circuit effect is intricately linked to the characteristics of SiC materials. Firstly, SiC materials possess elevated breakdown electric field strength, rendering the device susceptible to breakdown under high electric fields. This occurrence leads to a sharp increase in leakage current, subsequently triggering the short-circuit effect [7]. Secondly, the heightened carrier mobility intrinsic to SiC materials accelerates the migration of leakage current under high voltage, thereby further catalyzing the occurrence of the short-circuit effect. These attributes render SiC MOSFET devices more susceptible to the influence of the short-circuit effect, particularly within high-voltage and high-temperature environments.

In addition to material characteristics, oxide layer defects and surface states are also pivotal contributors to the short-circuit effect. The oxide layer plays a crucial role in SiC MOSFET devices; however, due to the heterogeneous structure of SiC materials, defects within the oxide layer often serve as conduits for leakage current, consequently inducing the short-circuit effect[8]. Furthermore, surface states on the oxide layer can also capture carriers, leading to an increase in leakage current.

Armed with a comprehensive understanding of the mechanisms underpinning the short-circuit effect in SiC MOSFET devices, researchers have proposed a series of suppression methods. On one hand, optimizing material fabrication processes to mitigate material defects can reduce the generation of leakage current. On the other hand, enhancing the quality and structure of the oxide layer to diminish the presence of defects and surface states also effectively suppresses the short-circuit effect. Additionally, methods such as optimizing device structural design and incorporating protective circuits can alleviate the impact of the short-circuit effect to a certain extent.

In conclusion, the short-circuit effect in SiC MOSFET devices arises from a confluence of factors encompassing material characteristics, oxide layer defects, and surface states. A profound comprehension of its occurrence mechanism empowers researchers to devise appropriate mitigation strategies, thereby augmenting the reliability and stability of SiC MOSFET devices and propelling their application within the realm of high-performance power electronics [9].

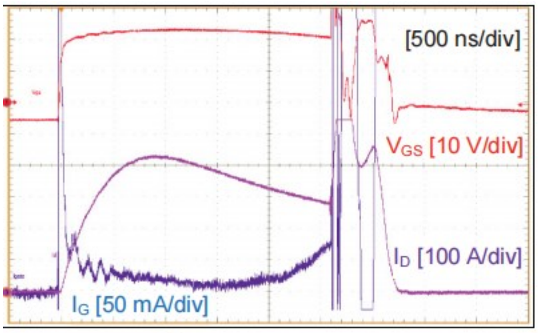

Figure 1. Schematic Diagram of a Short-Circuit [11]

3. Factors Influencing Short-Circuit Phenomenon

The factors influencing the short-circuit effect in Silicon Carbide (SiC) Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) devices are diverse and intricate, encompassing various aspects such as material characteristics, device structure, and operational conditions [10]. In-depth investigation into the short-circuit effect of SiC MOSFET devices necessitates the consideration of the interplay among these factors. The ensuing discussion will emphasize several pivotal influencing factors.

Firstly, material characteristics stand as one of the crucial determinants influencing the short-circuit effect in SiC MOSFET devices. SiC materials exhibit advantages like elevated breakdown electric field strength and heightened carrier mobility, albeit these attributes render them susceptible to a surge in leakage current. The elevated breakdown electric field strength contributes to an escalated impact ionization of electrons and holes under high voltages, thereby augmenting the leakage current. Additionally, the heightened carrier mobility accelerates the transportation speed of carriers along the leakage current path, thus exerting an influence on the magnitude of leakage current.

Secondly, the quality of the oxide layer and the presence of surface defects are pivotal factors influencing the short-circuit effect in SiC MOSFET devices. The oxide layer, serving as an insulating layer, plays a pivotal role within devices, and its quality directly impacts device performance. Defects within the oxide layer and surface states contribute to an increase in leakage current, thereby triggering the short-circuit effect. These defects can provide trap locations for carriers, engendering a surge in leakage current [11].

Furthermore, the design of the device structure also influences the short-circuit effect in SiC MOSFET devices. Optimizing the device structure can mitigate the concentration of electric fields, reduce the impact ionization of electrons and holes, and thereby suppress the surge in leakage current. For instance, by optimizing the distribution of electric fields and diminishing locally high electric field regions along the leakage current path, the occurrence of the short-circuit effect can be effectively mitigated.

Lastly, operational conditions are also among the factors influencing the short-circuit effect. Working temperature and voltage stress, among other environmental conditions, exert an impact on device performance. Elevated temperatures may accelerate defect generation and diffusion, thereby augmenting leakage current. Under high voltages, electrons and holes experience heightened electric field effects, potentially leading to more severe impact ionization and, consequently, an escalation in leakage current.

In summary, factors influencing the short-circuit effect in SiC MOSFET devices span material characteristics, oxide layer quality, surface defects, device structure design, and operational conditions, among other aspects. In further research and resolution of short-circuit issues in SiC MOSFET devices, a comprehensive consideration of the interplay among these factors is imperative to enable the reliable application of devices within the domain of high-performance power electronics.

4. Conclusion

This study offers a comprehensive analysis of the short-circuit effect in Silicon Carbide (SiC) Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) devices, shedding light on its influencing factors and mechanisms. The research highlights key conclusions: SiC material properties, like high breakdown electric field strength and carrier mobility, contribute to increased leakage current and susceptibility to breakdown. Oxide layer defects and surface states exacerbate this issue. Device structure design plays a role in the severity of the short-circuit effect, and operational conditions, especially high temperature and voltage, intensify it. To mitigate the short-circuit effect, optimizing material fabrication, improving oxide layer quality, refining device design, and implementing protective circuits are recommended. Ultimately, this research offers valuable insights for enhancing the stability and reliability of SiC MOSFET devices in high-performance power electronics applications, with the potential for future advancements in overcoming this challenge.

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